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Resonantly Enhanced Near-Field Lithography

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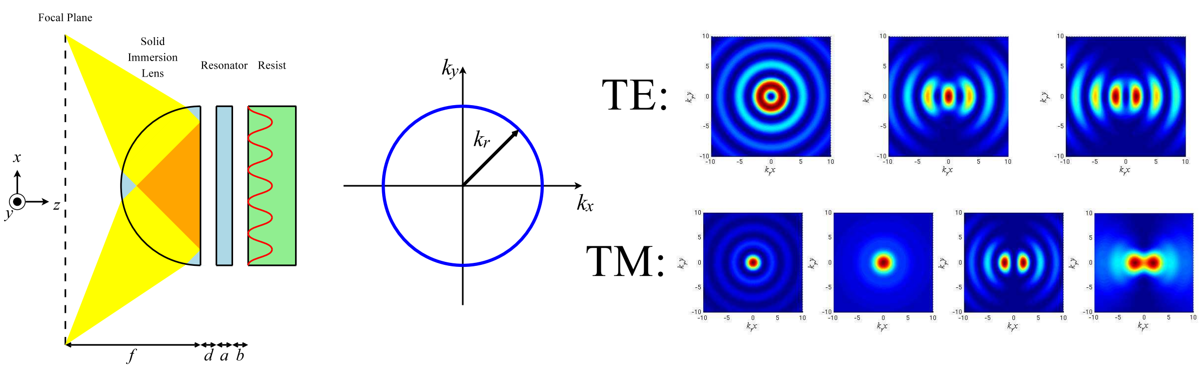
Abstract: We propose the combination of a planar optical resonator and a solid immersion lens for resonantly enhanced non-contact near-field lithography. Subwavelength small spots can be produced by exciting the Bessel modes of the resonator.

OCIS codes: (110.4235) Nanolithography; (230.5750) Resonators

1. Introduction

The Rayleigh-Abbe diffraction limit can be beaten if evanescent waves are used, but the exponential decay of evanescent waves poses a practical problem for lithography. Unlike propagating waves, however, evanescent waves can be amplified by a passive resonator. The near-field power transfer from the mask to the photoresist can be increased by orders of magnitude in the presence of a resonator, similar to the phenomenon of resonant tunneling [1]. We have recently formulated the general theory of resonantly enhanced near-field imaging [2], and found that the magnitude of resonant power transfer enhancement is proportional to the quality factor of the resonance, Q. This implies that low-loss dielectric photonic structures, such as slab waveguides and photonic crystals, are fundamentally superior to the more lossy plasmonic structures for the enhancement of near-field power transfer. Planar photonic structures can also be combined with a solid immersion lens to convert far-field radiation to resonantly enhanced evanescent waves.

2. General theory



(a) (b) (c)

Fig. 1. (a) Schematic of resonantly enhanced near-field lithography. (b) In two dimensions, a continuum of azimuthally degenerate resonance modes are available for each resonant spatial frequency k_r. (c) Free-space intensity patterns of some of the Bessel resonance modes for the TE (top row) and TM (bottom row) polarizations. The electric fields, from top left to bottom right, are given by $\hat{\phi}J_1(k_r r)$, $[\hat{\phi}J_1(k_r r)]_x$, $[\hat{\phi}J_1(k_r r)]_{xx}$, $\hat{z}J_0(k_r r)+\hat{r}(\kappa/k_r)J_1(k_r r)$ in the limit of $k_r=\omega/c$, $\hat{z}J_0(k_r r)+\hat{r}(\kappa/k_r)J_1(k_r r)$ in the limit of $\kappa \gg \omega/c$, $[\hat{z}J_0(k_r r)+\hat{r}(\kappa/k_r)J_1(k_r r)]_x$ in the limit of $k_r=\omega/c$, and $[\hat{z}J_0(k_r r)+\hat{r}(\kappa/k_r)J_1(k_r r)]_x$ in the limit of $k_r \gg \omega/c$, respectively.

In contrast with the resonantly enhanced solid immersion microscope described in Ref. [2], here we study the reverse operation, namely the conversion of far-field radiation to evanescent waves via a solid immersion lens, followed by the near-field amplification by a planar resonator, which is loaded with the photoresist, as depicted in Fig. 1 (a). The power transmitted to the resonator and the photoresist is given by

$$P \propto \left|\frac{t}{1-r'\Gamma\exp(-2\kappa d)}\right|^2 \mathrm{Im}\{\Gamma\}\exp(-2\kappa d), \tag{1}$$

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where t is the field transmission coefficient from the lens to free space, r' is the reflection coefficient from free space to the lens, $\kappa = \sqrt{k_x^2 - \omega^2/c^2}$ is the decay constant of the evanescent wave in free space, k_x is the transverse spatial frequency, Γ is the reflection coefficient from the loaded resonator, and d is the distance between the lens and the resonator. If the magnitude of Γ, proportional to the loaded Q of the resonance, is much larger than $\exp(2\kappa d)$, the power is approximately

$$P \sim \left|\frac{t}{r'\Gamma}\right|^2 \mathrm{Im}\{\Gamma\}\exp(2\kappa d), \tag{2}$$

which increases exponentially with respect to d. On the other hand, if $\Gamma\exp(-2\kappa d)$ is much smaller than 1, we have

$$P \sim |t|^2 \mathrm{Im}\{\Gamma\}\exp(-2\kappa d), \tag{3}$$

which decays exponentially with d. It follows that there exists an optimal d (and also an optimal b) at which critical coupling occurs between the input wave and the dissipation in the resonator as well as the photoresist, such that the power transfer is optimally enhanced. Hence, the presence of a high-quality resonator enables efficient non-contact near-field lithography for resonant spatial frequencies.

3. Bessel resonance modes

As a simple and illustrative example, a dielectric slab waveguide can be used as the resonator. In the one-dimensional transverse spatial frequency domain, each slab waveguide resonance is approximately Lorentzian and well separated from one another. Thus, there is a trade-off between resonant enhancement and spatial bandwidth near each resonance. It would then seem that only patterns consisting of discrete spatial frequencies can be resonantly enhanced.

Because a slab waveguide is rotationally symmetric in the $x-y$ plane, however, waveguide modes exist as long as the transverse spatial frequency magnitude $k_r \equiv (k_x^2 + k_y^2)^{1/2}$ satisfies the resonance condition, so a continuum of azimuthally degenerate modes are actually available for each eigenvalue of k_r, as shown in Fig. 1 (b). Evanescent Bessel modes that resemble subwavelength small spots can result from the excitation of such modes. Some of the Bessel resonance modes are plotted in Fig. 1 (c).

4. Summary

In summary, we have proposed the combination of a planar dielectric resonator and a solid immersion lens for near-field lithography. Compared with other proposals, such as plasmonic or metamaterial lenses, the inherent low loss of dielectric structures enables efficient near-field power transfer to the photoresist. Although there is a trade-off between resonant enhancement and resonant bandwidth, the rotational symmetry of a planar resonator gives rise to Bessel modes, which allow important subwavelength patterns to be produced.

5. References

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